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NON-EQUIVALENCE FOR BEAN SEEDS OF CLOCKWISE AND COUNTERCLOCKWISE MAGNETIC MOTION: A NOVEL TERRESTRIAL ADAPTATION?[1]

FRANK A. BROWN, JR. AND CAROL S. CHOW

Department of Biological Sciences, Northwestern University, Evanston, Illinois 60201, and Marine Biological Laboratory, Woods Hole, Massachusetts

Jones (1960) reported that plant growth could be altered by uniform daily rotation. Clockwise rotation depressed growth and counterclockwise accelerated it. The basis of this phenomenon has remained unexplained.

Brown and Chow (1973a, b), investigating water uptake by bean seeds, reported that rate of water uptake varied from day to day in a manner unaccountable in terms of variations in any obvious environmental factors and yet two populations of samples concurrently investigated at two different sites could exhibit between them a high positive correlation ($r = 0.8$) under some circumstances and under other conditions a negative one. It was postulated that beans in their rate of water uptake could correlate either plus (+) or minus (−) with some biologically effective, subtle, uncontrolled geophysical parameter and that other ambient electromagnetic environmental conditions could influence the sign of the correlation.

It was reported further (Brown and Chow, 1973a) that beans in water in closely juxtaposed vessels could mutually bias one another to adopt opposite signs of their correlating relationship under some circumstances and the same sign under others. Beans in paired vessels on rotating platforms (6 rpm) were influenced in these interactions as follows: clockwise rotation favored mutual biasing to the same sign and counterclockwise rotation, to opposite sign. Interaction between beans was reported to be abolished in the weak field of a slowly rotating (1 rpm, clockwise from above) horizontal bar magnet.

An investigation of 'spontaneous' activity in hamsters maintained on platforms undergoing daily rotation (Brown and Chow, 1974) disclosed that these mammals, like the several kinds of plants studied by Jones and by Brown and Chow, are also influenced in opposite manner by clockwise and counterclockwise rotations and display a negative correlation between them in their systematic fluctuations in mean daily activity. Therefore, mammals, like the beans, were presumed to be capable of assuming either of two states, plus (+) or minus (−), in their day to day correlation with uncontrolled pervasive geophysical parameters and that clockwise rotation, other factors equal, favors the opposite sign from counterclockwise.

Experiments and Results

The following exploratory experiment was initially designed to learn whether a rotating magnetic field would influence the rate of water uptake in beans and

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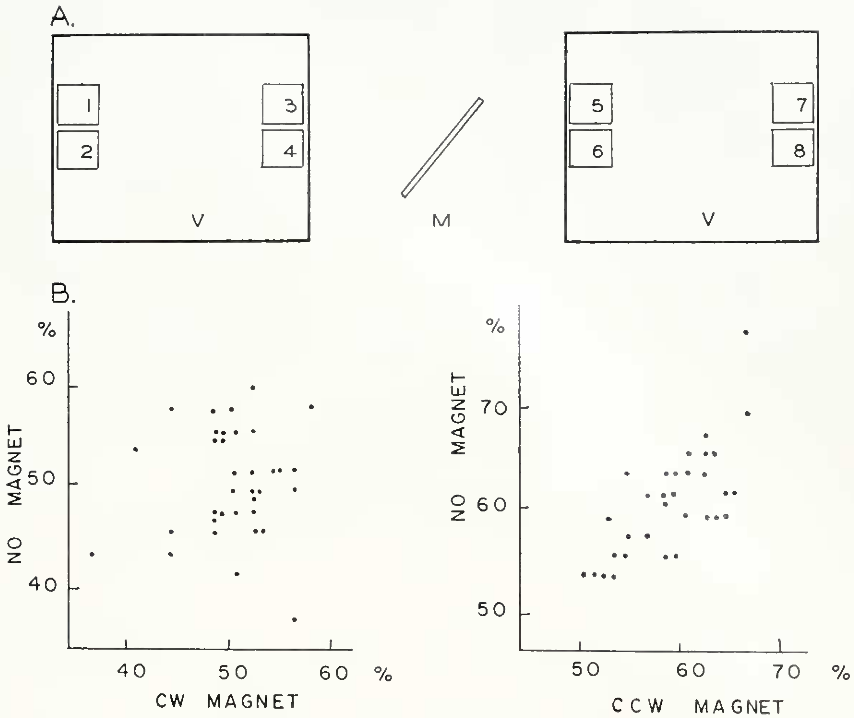

FIGURE 1. A) The experimental arrangement used in the initial study. 1–8 are eight 20-bean samples in aluminum screen trays; V, large, plastic vessels; M, rotating, 18-cm, Alnico bar magnet (present for experimentals but absent for controls. B) Scatterplot for relationship between day-to-day values for controls, and experimentals in field of a clockwise-rotating magnet, and the same for a counterclockwise-rotating magnet. The values on the axes indicate the percentage increase in weight of the seeds for 4 hours in water.

if so, in what manner and degree. The surprising outcome, however, appears to have revealed a reference environmental parameter which has been involved in the differentiation by organisms of clockwise and counterclockwise rotational directions. In each of two areas in a large laboratory room, about 15 meters apart, four pairs of 20-bean groups in shallow 6 × 6 cm aluminum screen baskets (Figure 1A, 1–8) were arranged in water in two large plastic vessels (Figure 1A, V). For one group an 18 cm rotating (2 rpm) Alnico bar magnet was centered (Figure 1A, M) between the two large vessels. The other 4-pair setup was a duplicate except for absence of a magnet, and comprised the control. All beans came from the same initial stock supply. The temperature of the air-conditioned laboratory was regulated to less than ±1° C.

On each of 35 days distributed over the period May 15 through July 3, 1972, the percentage weight increase through water uptake in beans was determined during a precisely timed initial 4 hours following submergence. This was accomplished through measurement of initial and final wet weights. The amount of water absorbed was expressed as a percentage increase in weight of the initial dry seeds. The 4-hour period always spanned the noon hour. For the experimentals (with magnet) the direction of rotation was clockwise (viewed from above). During an additional 32 days over the interval July 4 through August 18, 1972, the experiment differed only in that the direction of magnet rotation was counterclockwise. The strength of the horizontal vector of the experimental field effected, at the experimental location, about a ±80° oscillation in a compass needle at the positions of the outermost pairs and effected, of course, a 360° complete slave rotation at the location of the innermost pairs.

Correlating the day by day mean rates of water uptake for the experimentals with that of the concurrent controls for the interval when magnet rotation was clockwise (Figure 1B) gave a standard deviation for the controls ±5.18%, experimentals ±4.40%, and r = +0.070 ± 0.169. In short, there was no significant correlation between the two groups. When, however, the possibility of a correlation was similarly examined for the interval when the magnet rotation was counterclockwise (Figure 1B), the standard deviation for the controls was ±5.19%, for experimentals ±4.58%, and r = +0.729 ± 0.083, a very highly significant correlation. Transforming the r's to z's to facilitate determination of statistical significance of the difference yielded, respectively, +0.070 ± 0.176 and +0.927 ± 0.185. The difference between these two was 0.857 ± 0.255, a value highly significantly different from zero ($P < 0.001$).

Providing a parallel, secondary control over the total period of the rotating magnet study, located in the same large laboratory room, and involving beans from the same stock supply were two more experimental series, intermingled with one another, each with six aluminum-screen baskets containing 20 beans. For these, each basket was submerged in a separate small plastic vessel. One group comprised three pairs of juxtaposed vessels; the other group constituted six vessels each separated from any other by at least 70 cm. The day-to-day means for all twelve of these vessels of beans over the period of the present investigation were calculated. When these values were correlated with those of the concurrent specific primary controls for the rotating magnet series a strong positive value was obtained. This positive correlation between the primary and secondary controls continued unmodified throughout the intervals when the correlation was abolished by the clockwise magnet rotation and was unaffected by the counterclockwise.

Despite the slightly different experimental set-ups, from May 15 through August 18 the two controls, primary and secondary, correlated strongly over the whole period, $r = +0.738 \pm 0.055$ ($N = 67$). They also correlated highly significantly over *both* the period of clockwise magnet rotation ($r = +0.527 \pm 0.122$, $N = 35$) and counterclockwise rotation ($r = +0.603 \pm 0.113$, $N = 32$), exhibiting no significant difference in the degree of plus correlation between the two periods. Standard deviation for the secondary controls over these two periods were, respectively, ±5.03% and ±5.54%, again with neither a significant difference between one another nor with the primary controls.

All these findings support the assumption that the times of the two rotating-magnet series were essentially equivalent to one another and did not alter qualitatively between the two successive segments of the year. These comparative values also support the presumption that the observed abolition of the correlation was actually effected by the presence of the clockwise-rotating magnetic field, an effect not similarly produced by the counterclockwise field during which time no statistically significant difference occurred between the r of experimental *vs.* primary control ($+0.729 \pm 0.083$) and the r of the primary *vs.* the secondary control ($+0.603 \pm 0.113$).

While it could not be concluded unequivocally that both clockwise and counterclockwise magnet rotation would have abolished the correlation during the first period and neither would have done so during the second period this seemed improbable and to be a postulation unnecessarily complex at this juncture. A second experiment, performed to check directly the foregoing conclusions, removed this doubt.

This second experiment was performed between January 21 and May 2, 1974, with another lot of beans with significantly lower mean rate of water uptake. For this one, three large circular wooden tables were used. These were at least five meters from one another. Two of the tables had at their centers an 18 cm horizontal bar magnet; one rotated clockwise two rpm, and the other counterclockwise one rpm. The third table, without a magnet, served as a simultaneous control (Figure 2A). Four pairs of small plastic dishes each containing 20 beans in water were placed equidistantly around and 40 cm from the center of each table. The experimental horizontal magnetic fields at the positions of the beans were close in strength to the earth's. A total of 72 such experiments were run on as many days over the three-month period.

Correlating all 72 values of mean bean water-uptake rates on each of the two tables bearing the rotating magnets, with the controls, yielded the scatterplots depicted in Figure 2B. The coefficient for the clockwise magnet was +0.0135 and for the counterclockwise magnet was +0.397. Transforming these values to z, the difference between them was 0.406 ± 0.169 ($P < 0.02$). Excluding for the clockwise table, those twelve values lying below 14.0 and above 23.0 the coefficient became negative, $r = -0.267$, and the difference between the z's was 0.694 $\pm$ 0.178 ($P < 0.001$). This manner of exclusion of values would not itself be expected to impose any correlation upon truly random data.

The difference between the variances for beans within the clockwise and counterclockwise rotating fields of the magnets was significant ($F = 1.79$; $P < 0.01$). It was not identifiable in the immediate study whether this difference arose from the direction of rotation of the magnet *per se,* or from other specific characteristics of the particular laboratory location.

Other experiments with bean water-uptake on rotating platforms and in the fields of rotating magnets were performed during the summer of 1974 at the Marine Biological Laboratory, Woods Hole, Massachusetts. The room was air-conditioned to relatively constant temperature, $22 \pm 1\frac{1}{2}°$. Special care was taken in timing the four-hour runs in water; the beans were all counted out in their screened trays, and labeled, in advance of their submersion in water. The submersions were made in sequence around the tables, while all systems were operating, one after another at one minute ($\pm$ ten seconds) intervals. Exactly four hours later $\pm$ ten seconds, each tray was assayed, similarly one minute apart. Five tables, about 92 cm in diameter, were employed on a wooden bench. Four possessed a reversible gear-motor, electrically driven, to rotate either the whole table or an 18 cm bar magnet at its center. The directions of rotation, clockwise and counterclockwise, were

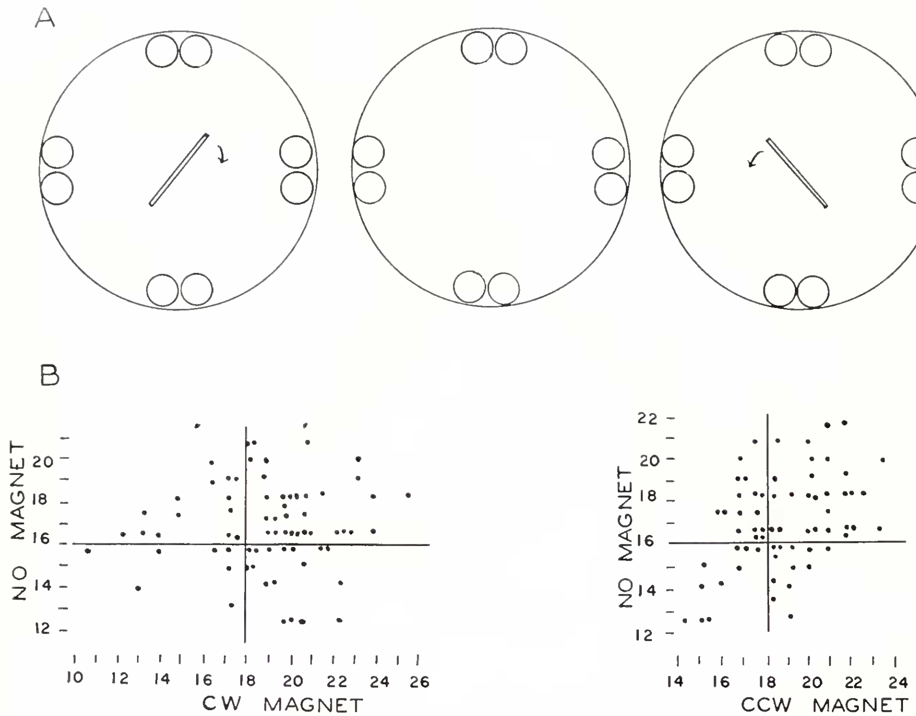

FIGURE 2. A) The three conditions concurrently operating in the second experiment. Small circles on the larger tables indicate plastic dishes (9 cm in diameter) each containing 20 beans in aluminum screen trays. B) Scatterplots show relationships between day-to-day percentage values for clockwise and counterclockwise tables relative to the common controls.

alternated between the two rotating tables and two rotating magnets on consecutive days to compensate for any position effect.

On fifty days, five days a week between June 17 and August 23, 1974, experiments including both rotating tables and rotating magnets (both, 1 rpm) were performed. There were four pairs of vessels distributed around the edge on each table. There was also a comparable control table, non-rotating and without a magnet. The day-by-day data were converted to deviations from the daily means of all sixty vessels of beans being measured concurrently in four experiments in the room because of relatively substantial systematic variations occurring in water uptake rates over the summer.

When the means for the control and clockwise rotating tables were correlated (with one of the 50 points which was widely discontinuous with the mass of points, omitted), the clockwise table gave a very low negative value, $r = -0.078$ (Figure 3A), while the counterclockwise table yielded a statistically highly significant negative value, $r = -0.534$ (Figure 3B). After transforming these to z's, the difference between them was found to be 0.518 ± 0.208, $P < 0.02$.

Now, doing the same for the rotating magnet series, counterclockwise magnet rotations (Figure 3C) gave a positive but statistically insignificant value, $r =$

+0.144. Clockwise magnet rotation, on the other hand, yielded a still smaller positive value, $r = +0.039$ (Figure 3D). Indeed, the variance on the clockwise magnet table was higher than for the counterclockwise one ($F = 1.83$; $P < 0.05$), just as had been discovered for a comparable experiment performed earlier in Evanston. However, an inspection of the scatterplot of the relationship suggested that as the clockwise values increased above, or fell below, the mean of the values obtained for the day the values of the stationary controls increased proportionately. Indeed, correlating the values of the clockwise magnet table, without regard to sign, with the values from the control table yielded $r = 0.411$, or $z = 0.437 \pm 0.145$.

It is evident that either continuation of the negative correlation of the clockwise beans below their mean, or of the positive correlation above it, would have effected a very substantially altered rate of water uptake relative to the control.

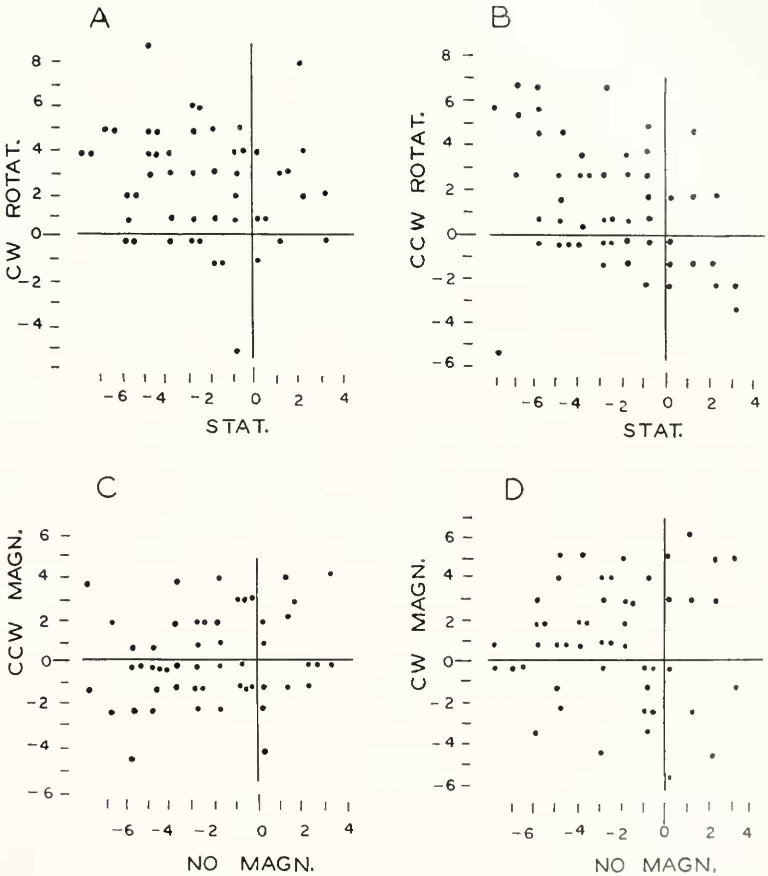

FIGURE 3. Results of studies of beans on rotating (1 rpm) and stationary platforms, and in the field of a very weak rotating magnet (1 rpm) during the summer of 1974. Scatterplot A shows means for those beans on clockwise table *vs.* ones on a stationary one; *B*, same for beans on counterclockwise platform; C, same for beans in field of counterclockwise-rotating magnet; D, same for beans in field of a clockwise-rotating magnet.

The change in sign of the correlation with the exogenous effective parameters seems, therefore, probably to be an adaptive behavior for the maintenance of a relatively constant state.

Most important of all, in this last experimental series, there is a remarkable confirmation and extension of the results obtained earlier in our Evanston laboratory. Counterclockwise magnetic field rotation results in an opposite sign of correlation with the concurrent stationary control to that found for counterclockwise table rotations in the earth's magnetic field (Figure 3, B and C). These two are highly significantly different from one another. The difference between their z's is 0.740 ± 0.206, $P < 0.001$. For the actual values for the two, we must recall that in dealing with deviations from the daily means with groups of the size of the present series instead of with actual values such as could be used for Figures 1 and 2, the null expectation is a negative correlation of the order of about $r = -0.2$. We get, therefore, in this series a direct answer to a hypothesis that for the beans a magnetic field rotating counterclockwise will produce effects which are the opposite of those observed for organisms rotating counterclockwise in the earth's relatively static vector field.

Now examining the clockwise magnetic field effect (Figure 3D), we see an apparent active sign reversing system which results in essentially no overall correlation with the controls. In retrospect, this is what one can note for the same relationships in Figures 1 and 2. Clockwise rotation of a magnetic field appears to unstabilize the sign of response, possibly in part by dissociating the organism from environmental factors which normally determine it. The distributions of points in scatterplots 3A and D are quite different one from the other, though only dubiously suggesting opposite effects.

Discussion

The asymmetrical magnetic response is consistent with the previously described differences between influences of clockwise and counterclockwise platform rotation in the earth's natural atmosphere for which, incidentally, no hypothesis as to causative basis has been advanced up to the present. It is also consistent with the earlier demonstrations in a number of laboratories of organismic responsiveness to vector directional differences in extremely weak magnetic fields in which organisms were used ranging from Paramecium (Brown, 1962) and Volvox (Palmer, 1963) through worms and snails (Brown, 1971) and insects (Picton, 1966; Lindauer and Martin, 1968; Wehner and Labhart, 1970) to European robins and homing pigeons (Wiltschko and Wiltschko, 1972; Walcott and Green, 1974), fishes (Becker, 1974), and gerbils (Stutz, 1971).

In the present studies, clockwise rotation of the magnet appeared to render essentially random, or forced to opposite sign in part or in whole, the relationship of bean water uptake to the effective concurrent geophysical fluctuations, resulting in nearly equal distribution of plus (+) and minus (−), or a preponderance of opposite, signs in correlating state in the clockwise magnet experimentals relative to the controls. On the other hand, counterclockwise rotation of the magnet had little or no influence on the correlating sign which was therefore predominantly free to be determined by environmental parameters which parallelly influenced the experimentals and controls.

These results are consistent with an earlier published report (Brown and Chow, 1973a) that members of rotating pairs tend to adopt the same sign when on a platform undergoing clockwise rotation if we postulate that counterclockwise magnet rotation provides an influence the equivalent of clockwise platform rotation in the earth's magnetic field. And contrariwise, clockwise magnet rotation provides the equivalent of counterclockwise platform rotation which was earlier reported to result in a statistically significant reduction of plus correlation between members of pairs. The results also confirm earlier findings that clockwise magnet rotation abolished correlations between members of paired dishes of beans.

A hypothesis is supported that counterclockwise magnet rotation at 1 rpm has relatively little effect on the sign determination of the organism's correlation with fluctuations in effective but still unidentified atmospheric field parameters. A positive correlation is evident with untreated controls. Quite the opposite effect is produced by counterclockwise rotation of the organisms at the same place and time; this now effects the opposite sign, or a negative correlation with non-rotating controls.

Whereas simultaneous clockwise and counterclockwise table rotations at 1 rpm tend to yield opposite results relative to one another, that is, clockwise table rotation favors a correlation with controls which is basically positive, the clockwise magnetic field rotation provides a correlation which in three experiments was of lower positive value, and indeed, one in which the structure of scatterplots seems to contain a good degree of a negative relationship within them. Therefore, all the results of these experiments are consistent with a hypothesis that effects noted on clockwise and counterclockwise rotating tables are in good measure a consequence of the organism steadily and systematically being altered in their orientation to the geomagnetic fields. It is predicted that further experiments will give firm support to this hypothesis.

All these findings also provide support for the postulation that altered, extremely weak, electromagnetic fields have been responsible for the previously described either low positive or significant negative correlations between bean water uptake inside and just outside a metal-sheathed walk-in constant temperature chamber (Brown and Chow, 1973a, b), under otherwise apparently similiar conditions. They also provide support for a hypothesis that the rather substantial reported differences in hamster activity (Brown and Chow, 1974) between two rotational directions, at one revolution per day, are effected by the continuous clockwise and counterclockwise animal motions relative to the geomagnetic field.

Such differences in effects between directions of magnetic motion, often even effecting essentially opposite responses, constitute still another reason why the capacity of living creatures to sense the terrestrial electromagnetic fields so long eluded disclosure. At the same time, such a particularized difference encourages speculation that such weak atmospheric electromagnetic forces are playing vital roles for living systems in biological regulations including the enigmatical clocks. We postulate that the asymmetrical magnetic response is an adaptation of life to its rotating and sun-orbiting planetary environment.

Quite a substantial range of variation in rates of a biological process continuing in what have earlier been presumed to be constant conditions for organisms appear able to result from responsiveness to subtle, pervasive geophysical parameters. It is evident, therefore, that such a capacity as that for a sign-changing relationship to fluctuations in atmospheric electromagnetic fields can be a very effective contributing factor for homeostasis. It is interesting to note that the differing mean rates of water uptake for both experimentals and controls evident in Figure 1B depict two portions of a persistent annual variation which has now been followed through two years in two different lots of beans, and which simultaneously contains a significant mean synodic monthly component, as well.

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Summary

1. Three experiments on water-uptake in pinto beans, *Phaseolus vulgaris,* during their first four hours in water have all indicated that clockwise and counterclockwise rotating magnetic fields have statistically significantly different effects upon the rate of the process.

2. The results suggest that this difference is independent of time and place. Critically performed experiments at Evanston, Illinois and Woods Hole, Massachusetts, over more than a two-year span, all gave essentially the same results.

3. A clockwise rotating magnetic field abolished, for the beans, a correlation with concurrent control beans without magnet, while a counterclockwise rotating magnet failed to do so.

4. In a concurrent series involving rotating beans (1 rpm, clockwise and counterclockwise) and beans in fields of a weak rotating magnet (1 rpm, clockwise and counterclockwise), the effects of counterclockwise magnet and counterclockwise table rotations were of opposite character and highly significantly different from one another. Effects of clockwise magnet and clockwise table rotations differed significantly, in turn, from their opposite directions of rotations.

5. The results uniformly support the hypothesis that the different effects reported between clockwise and counterclockwise rotation of organisms result from their systematic, directional motions relative to the geomagnetic field.

6. It is postulated that this non-equivalence for organisms of clockwise and counterclockwise rotations of such extremely weak magnetic fields reflects a novel and fundamental adaptation of organisms to their rotating and sun-orbiting environments.

LITERATURE CITED

Becker, G., 1974. Einfluss des Magnetfelds auf das Richtungsverhalten von Goldfischen. *Naturwissenschaften,* **61**: 220–221.

Brown, F. A., Jr., 1962. Responses of the planarian, *Dugesia,* and the protozoan, *Paramecium,* to very weak horizontal magnetic fields. *Biol. Bull.,* **123**: 264–281.

Brown, F. A., Jr., 1971. Some orientational influences of nonvisual, terrestrial electromagnetic fields. *Ann. N. Y. Acad. Sci.,* **188**: 224–241.

Brown, F. A., Jr., and C. S. Chow, 1973a. Interorganismic and environmental influences through extremely weak electromagnetic fields. *Biol. Bull.,* **144**: 437–461.

Brown, F. A., Jr., and C. S. Chow, 1973b. Lunar-correlated variations in water uptake by bean seeds. *Biol. Bull.,* **145**: 265–278.

Brown, F. A., Jr., and C. S. Chow, 1974. Phase shifting an exogenous variation in hamster activity by uniform daily rotation. *Proc. Soc. Exp. Biol. Med.*, **145**: 7–11.

Jones, R. L., 1960. Response of plants to a uniform daily rotation. *Nature*, **185**: 775.

Lindauer, M., and H. Martin, 1968. Die Schwereorientierung der Bienen unter dem Einfluss des Erdmagnetfeldes. *Z. vergl. Physiol.*, **60**: 219–243.

Palmer, J. D., 1963. Organismic spatial orientation in very weak magnetic fields. *Nature*, **198**: 1061–1062.

Picton, H. D., 1966. Some responses of *Drosophila* to weak magnetic and electrostatic fields. *Nature*, **211**: 303.

Stutz, A. M., 1971. Effects of weak magnetic fields on gerbil spontaneous activity. *Ann. N. Y. Acad. Sci.*, **188**: 312–323.

Walcott, C., and R. P. Green, 1974. Orientation of homing pigeons altered by a change in the direction of an applied magnetic field. *Science*, **184**: 180–182.

Wehner, R., and Th. Labhart, 1970. Perception of the geomagnetic field in the fly, *Drosophilia melanogaster*. *Experientia*, **26**: 967.

Wiltschko, W., and R. Wiltschko, 1972. Magnetic compass of European robins. *Science*, **176**: 62.